HEAVY MOVABLE STRUCTURES, INC.
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Noteworthy Aspects of the East Michigan St. Hydraulic Rehabilitation

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MARRIOTT'S RENAISSANCE HOTEL AT SEAWORLD
ORLANDO, FLORIDA

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Bridge Background

History & Background

The Michigan St. Bridge in Milwaukee, Wisconsin is a tabletop type vertical lift bridge built in 1978 replacing a double leaf bascule bridge built in 1910. It provides four lanes of traffic and two sidewalks at the crossing over the Milwaukee River. The bridge is a multi-girder structure with a 73 foot length, 48 foot width and an original weight of approximately 402,000 pounds. The bridge is frequently operated with up to 10 lifts per hour during peak season and 11,500 vehicles per day on average. The bridge deck, superstructure, electrical systems, and hydraulic operating machinery were all replaced as part of a rehabilitation to modernize the bridge. This paper will provide background on how the existing hydraulic and machinery systems worked, how they were replaced with a discussion of many of the challenges and design choices used to overcome them. Finally, construction photos and a discussion of the challenges building and commissioning the system are included.

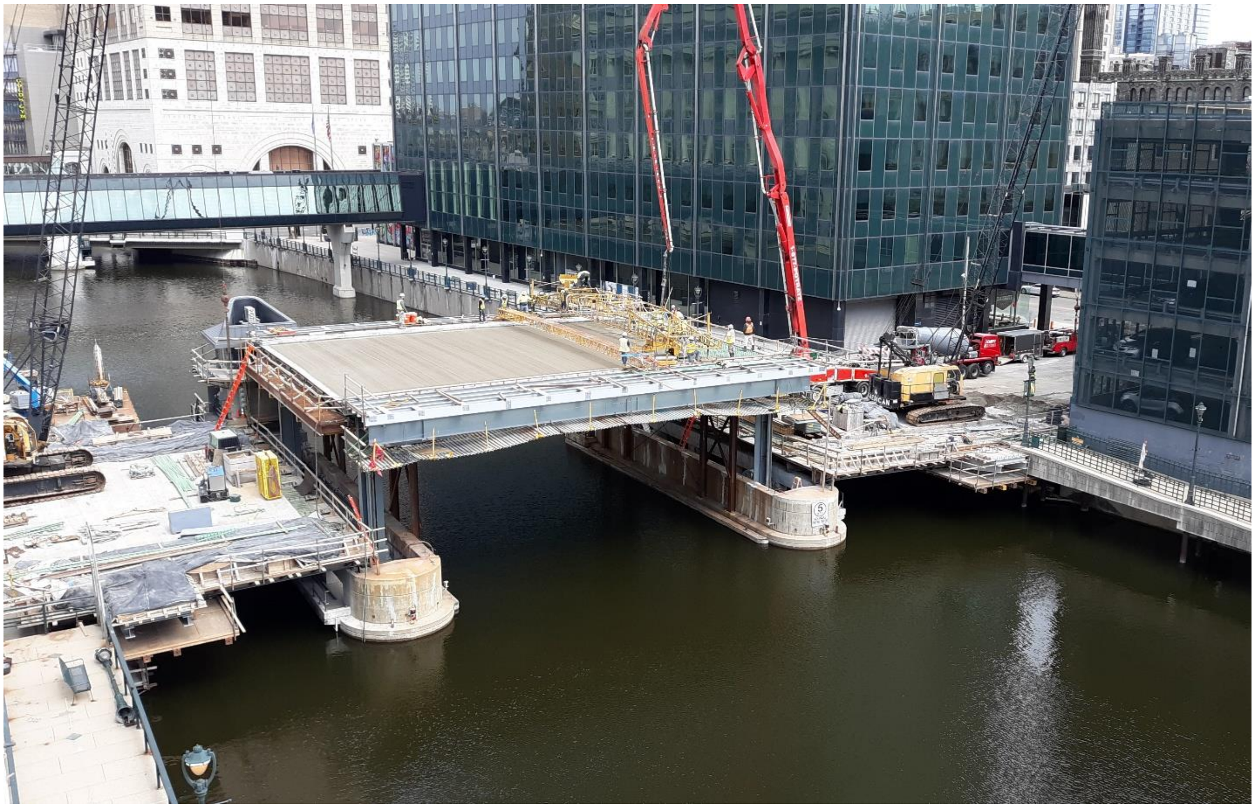

Photo 1: The Rehabilitated Bridge During the Deck Pour

Original Design

The bridge is a towerless vertical lift type structure, it is hung from sheaves in counterweight pits inside either abutment next to the channel and counterbalanced. The counterweights are hung from ropes installed on the end of lifting legs attached to each leg of the bridge (shown in cyan). Each abutment had one single acting hydraulic cylinder located beneath the centerline of the bridge (shown in blue) and each corner was synchronized using four equalizing drums which tied one lifting leg to the opposite corner of the span (shown in red, orange, yellow, and green). Two corner/legs were attached to each drum and guaranteed each corner was always paid out the same amount of rope keeping the bridge from tipping.

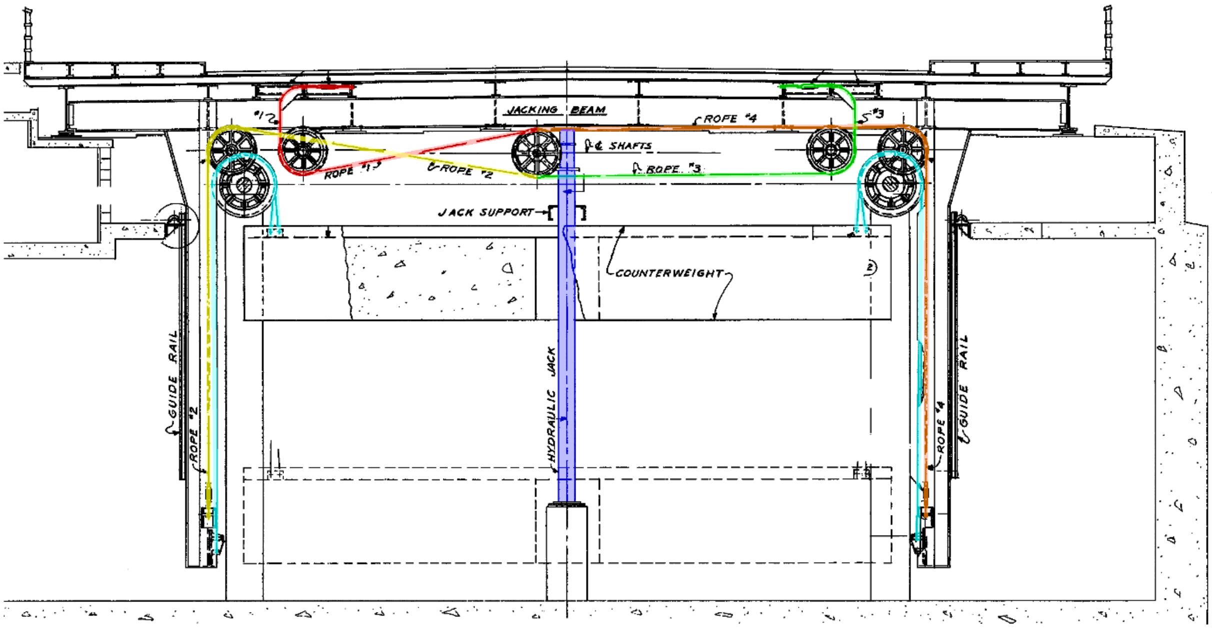

Photo 2: Cross Section of the Bridge Through the Pier

The hydraulic system was built by the Dover Corporation's elevator division and installed by the Northwestern Elevator company. The hydraulic system was a very simple design used for elevator systems. The system was designed to operate at 372 psi with a relief setting of 465 psi. It had a 40HP primary pump, 7.5 HP backup pump and two manifolds with control valves to provide redundancy. Each manifold included a strainer, relief valve, check valve, unloading valve and two speed solenoid operated raise and lower valves. The two-speed lowering valve allowed up to 215 GPM, while both raise and lower valves provided a "leveling speed" intended to do the final alignment of an elevator to a floor to be used as creep speed. Both the unloading and lowering valves included manual overrides to permit the bridge operation on the main pump with an unloading valve solenoid failure and to permit the bridge to be lowered in the event of a power outage or motor failure.

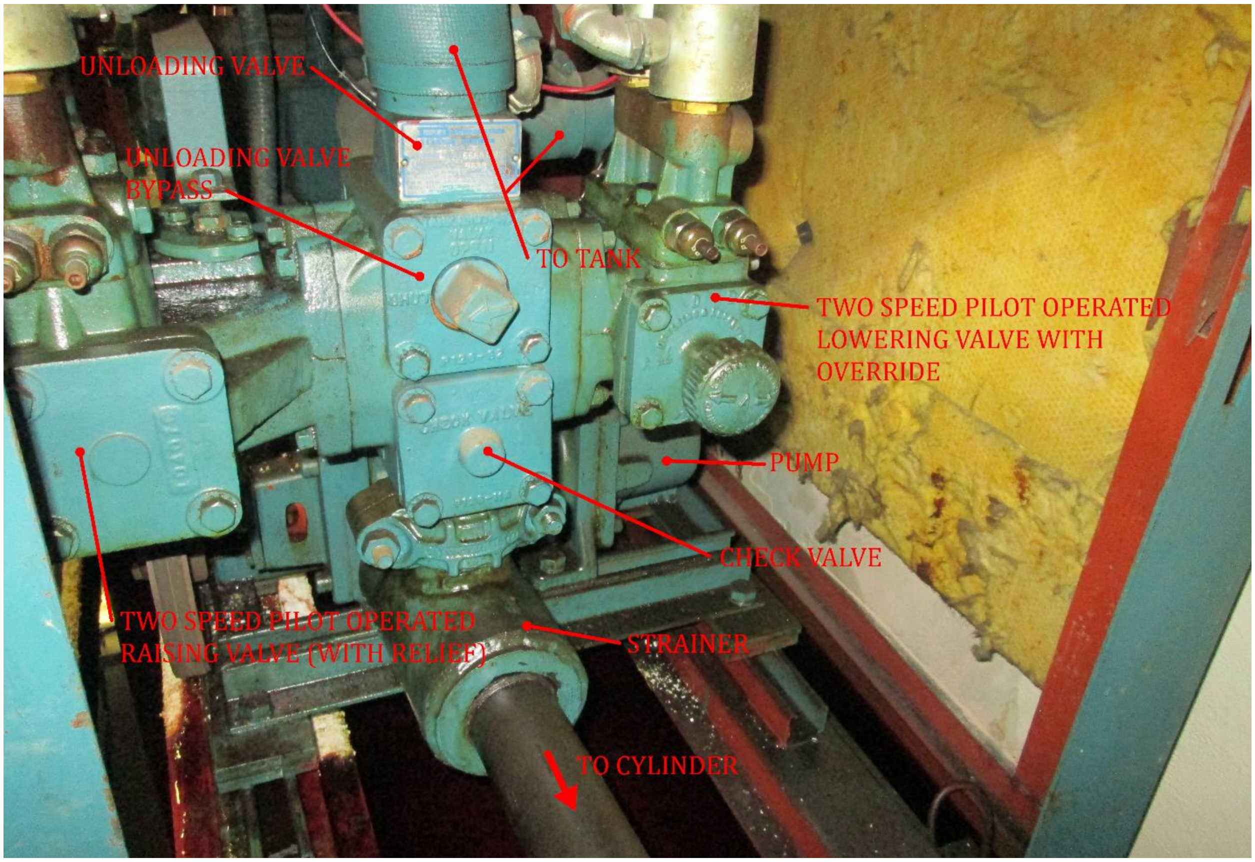

Photo 3: Control Valve Arrangement

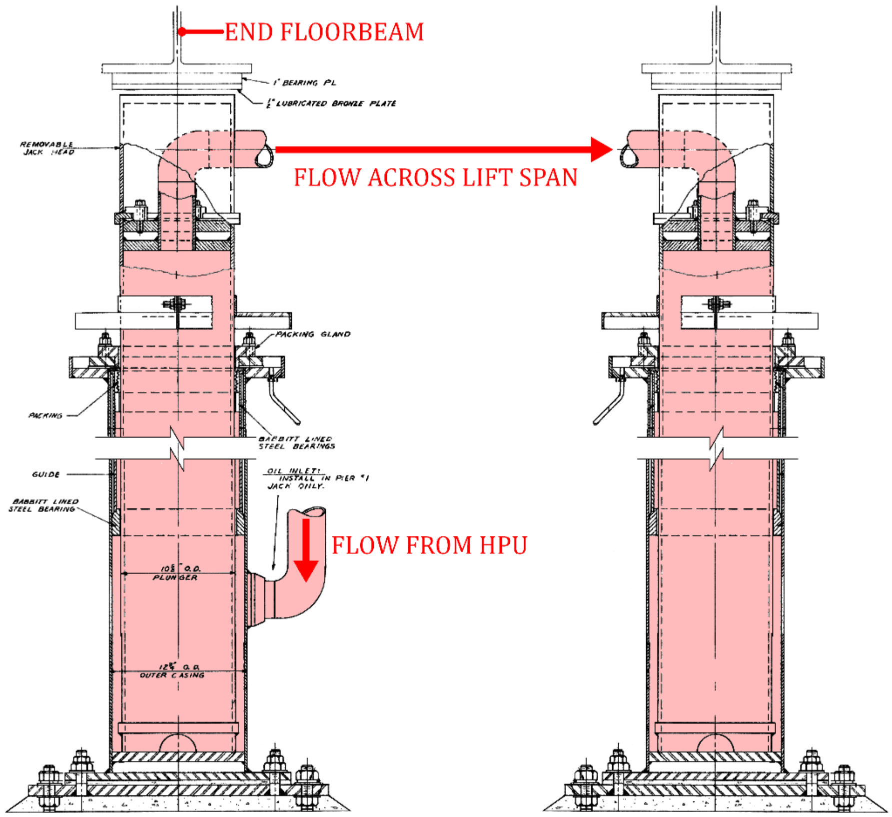

Photo 4: Single Acting Lift Cylinder Arrangement

Existing Conditions

There were numerous leaks in the existing system including at the pumps, valves, cylinders, and threaded pipes joints, many of which had become severe. The system pressure relief was designed to be set at 465 psi for the 400psi rated cylinders, however the system operated at 600psi. Although the cylinders did not require hoses due to the use of ball joints for flexibility and the use of the cylinder rods motion to transfer oil to and from the span, the system did not have cylinder manifolds with valves to lock of the cylinders in case of a pipe failure which does not meet the requirements of current revisions of AASHTO. While many items could be considered grandfathered there are certain safety requirements which should not be overlooked. AASHTO section 7.5.12.5 states “Cylinder Circuits shall include a cylinder manifold mounted directly to each cylinder used for span operation. Manifolds shall contain pilot operated check valves or similar means to hold fluid in the cylinder when the cylinder is not intended to be in motion. Manifolds shall also contain cylinder relief valves for limiting pressure to both ends…of the cylinder.” In addition to the deficiencies present in the system, the hydraulic system was approximately forty years old and had significantly exceeded the predicted life for all components based on table 2.9.1-1 of the AASHTO Inspection Evaluation and Maintenance Manual.

Photo 5: Existing Equalizer Drum and Hydraulic Cylinder.

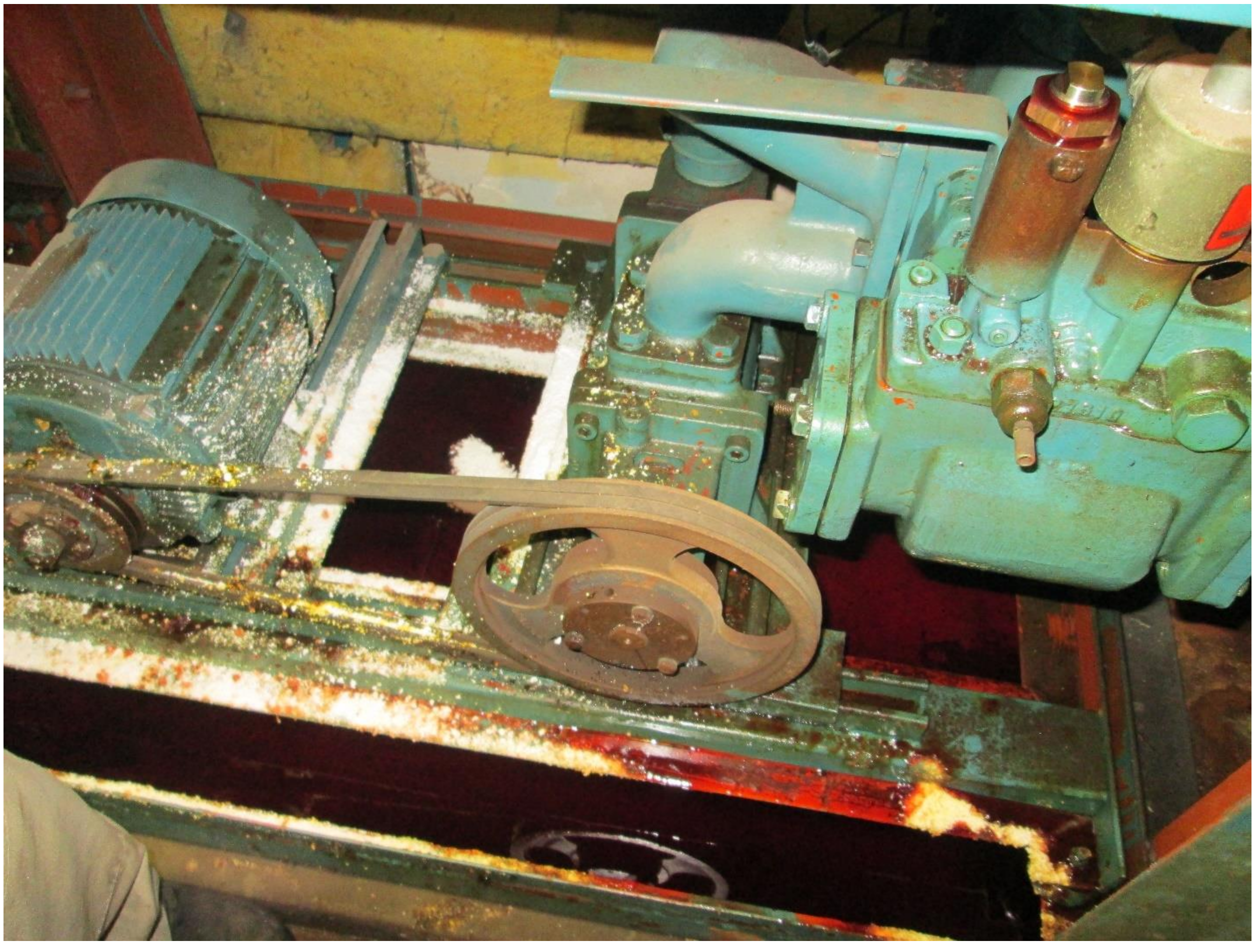

Photo 6: Leaks at the existing Hydraulic Power Unit

New Design

Design Constraints

The new design had many design constraints which had to be considered given the location and frequent use of the bridge by both boat and vehicle traffic. Milwaukee has a cold climate and its roads are salted in winter which makes the pit area below the roadway joints on this bridge a very corrosive environment. This necessitated the elimination of the equalizer system used to keep the bridge level during operation. To accomplish skew control four cylinders were used in lieu of the original two, and their positions would need to be synchronized with tight tolerances. The cold winters and warm summers make the choice of hydraulic fluid properties important to limit friction losses on colder days and keep all viscosities within component requirements during summer. The space available in the tender's house for electrical controls and hydraulic equipment is very limited. The bridge is limited to three phase 220v service by the power grid in the area severely limiting the amount of power the bridge can consume. The bridge needs a short cycle time to accommodate frequent boat traffic and the cylinder stroke makes buckling considerations a critical factor in system layout.

Flow Dividers

Simplicity and maintainability are key factors in any hydraulic system. To keep the hydraulic power unit out of the weather and in one location for troubleshooting the power unit was installed in the tender's house on one corner of the bridge. The compromise with a one HPU installations is that the pipe run to every cylinder varies in length significantly. Much consideration was given to synchronizing the cylinders mechanically with various types of flow dividers to make the system as simple as possible to maintain. The large system size required a flow divider that is built from gear pump components. Effectively 4 gear pumps would be stacked into one assembly with one shaft synchronizing the speed of all gears making each gear section displace the same amount of fluid to each cylinder independent of load. Although a positive displacement type of pump, gear pumps have some slip in which fluid bypasses the sides of the gear as a normal part of operation which allows the components to be lubricated. This is not normally an issue but can become noticeable with low speeds and high loads, or where very precise fluid control is required. To check the feasibility of a rotary flow divider for this application system pressure differences between the shortest and longest cylinder pipe runs were calculated at expected operating temperatures and the flow rates. These flow rates and pressure differences were used to choose a flow divider which would have the highest reasonable RPM to minimize slip. The amount of slip could be carried through the system to determine the difference between cylinder strokes over one operation. Given the large size of the flow divider, lack of available slip data on large flow dividers, and skew requirements for the project, no manufacturer could commit to manufacturing a flow divider that would provide better than several inches between cylinders within the same pit and electronic means of synchronization were ultimately used for the project.

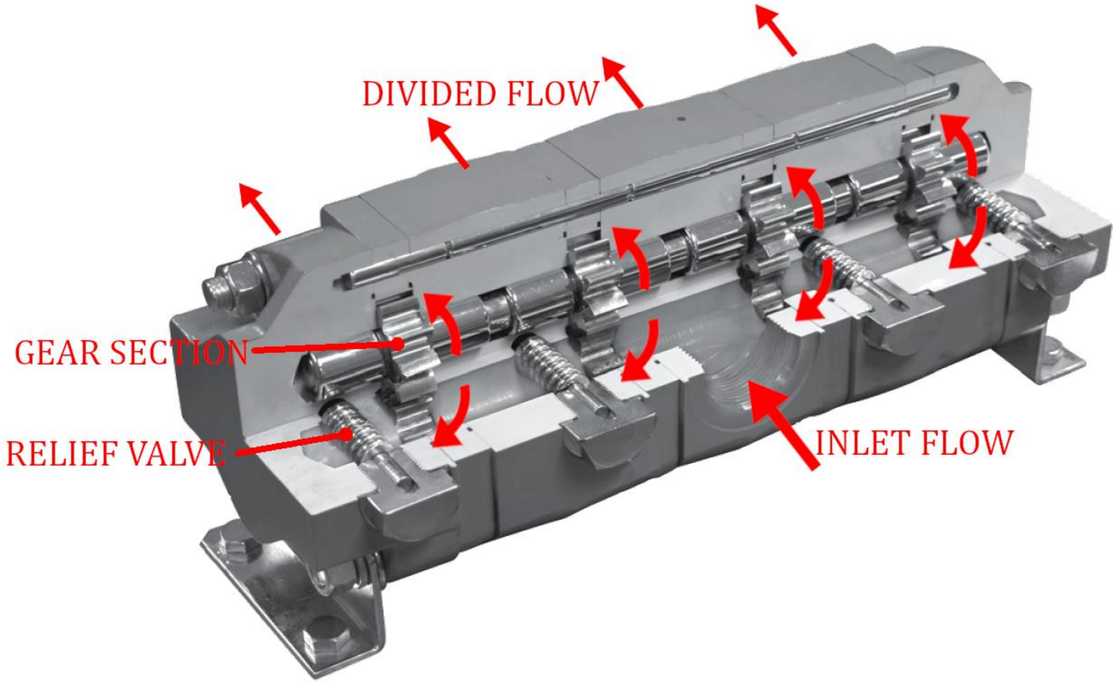

Photo 7: Basic Operation of a Rotary Flow Divider

Regeneration on Demand

Numerous factors determined the system power and ultimately the decision to use a regeneration on demand configuration. The main drivers of this were the limited electrical service at the bridge limiting the bridge to 120HP, the city's preference to operate in 60 seconds, the need to reduce flow rate to the cylinders to reduce pipe sizes, and to reduce power losses given the oversized rod diameters required to meet buckling capacity, the lack of space in the equipment room for variable displacement pumps to reduce power, and the city's preference for simple gear pumps. Regeneration on demand addresses all these issues by introducing a valve which can change the mechanical advantage of the system. It provides a 60 second operating time under normal loads by connecting the rod and bore end of a double acting cylinder together. This causes the fluid in the rod end of the cylinder to be forced into the bore end of the cylinder as it extends reducing the flow requirements for a given speed at the expense of operating pressure. The cylinder acts as if were a single acting cylinder with a bore diameter equal to the rod diameter in this configuration. To meet full wind and ice loading which will only rarely happen a pressure switch detects when the system pressure is too high and disconnects the ends of the cylinders from each other causing them to return to double acting operation. This gives additional lifting capacity with a 96 second lift time. The configuration allows for the motors to be more efficiently utilized by matching the speed and load with the motor power, reducing the motor power requirements by approximately one third given the cylinder arrangement.

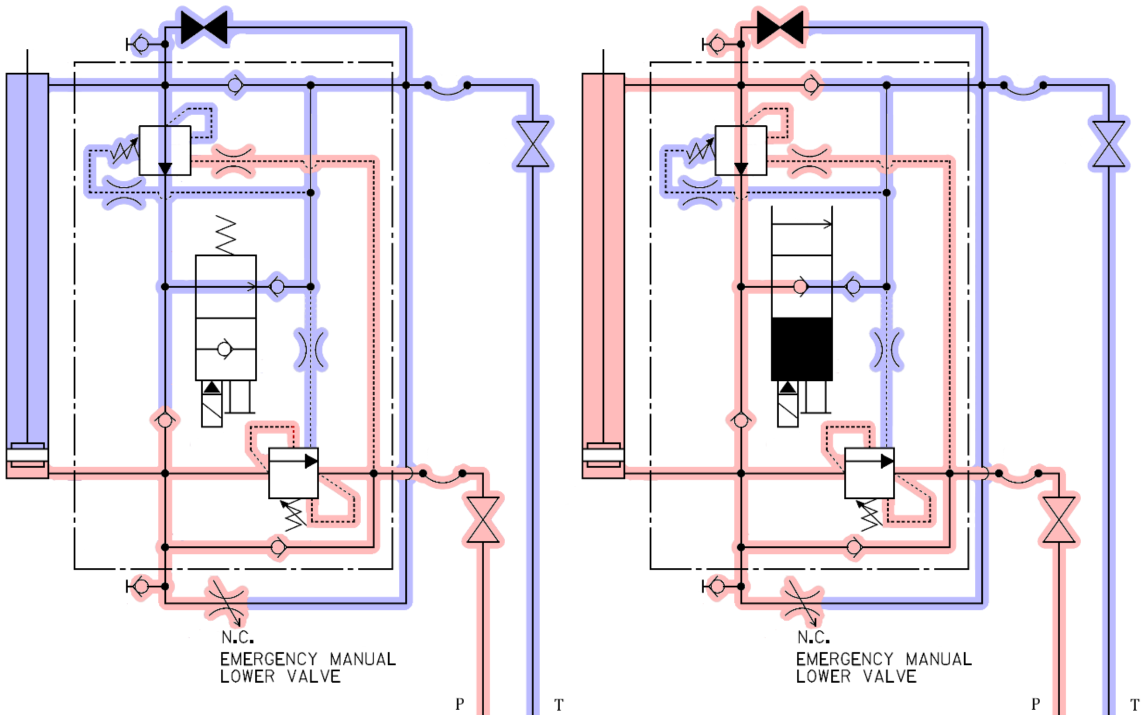

Photo 8: Raising Operation of a Regeneration on Demand Valve (Left: Non-Regeneration, Right: Regeneration Mode)

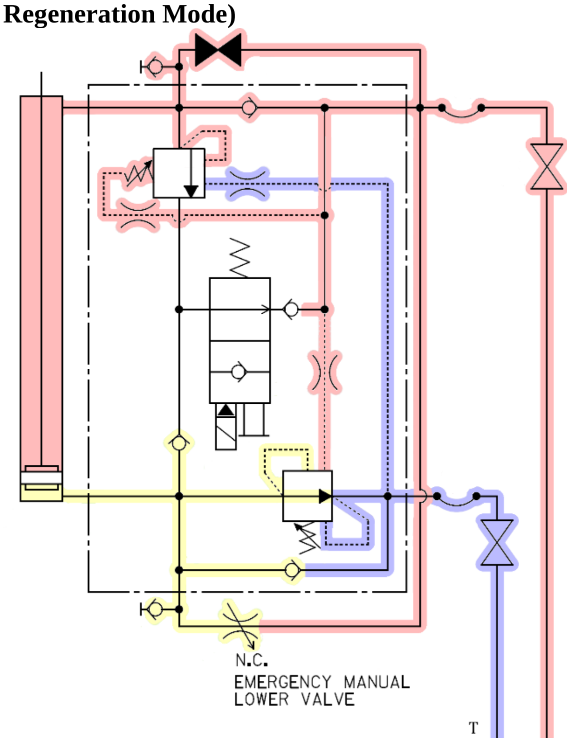

Photo 9: Lowering Operation of a Regen on Demand Valve Acting as a Counterbalance Valve

Benefits, Compromises, and Expected Performance

Given the stroke of the cylinders and compressive loading, buckling was the design driver for the cylinders. After sizing for buckling, the result is a low operating pressure and higher flow rate. A higher flow rate of results in larger pumps, but more importantly results in a larger reservoir since reservoirs are sized, in part, based on the flow rate of the pumps. The regeneration circuit overcomes these challenges without having to make compromises; it amplifies the operating pressure while reducing the required flow rate and subsequently reducing the required reservoir size. The decision was made to use a “regen on demand” circuit to provide additional capacity, recognizing that oftentimes there are changes made in the future that result in larger loads whether its weight increases, or friction changes. Regen on demand is a unique way to meet “Condition C” used in earlier versions of the AASHTO movable bridge design specifications since it reduces the speed of the bridge while providing increased force capability.

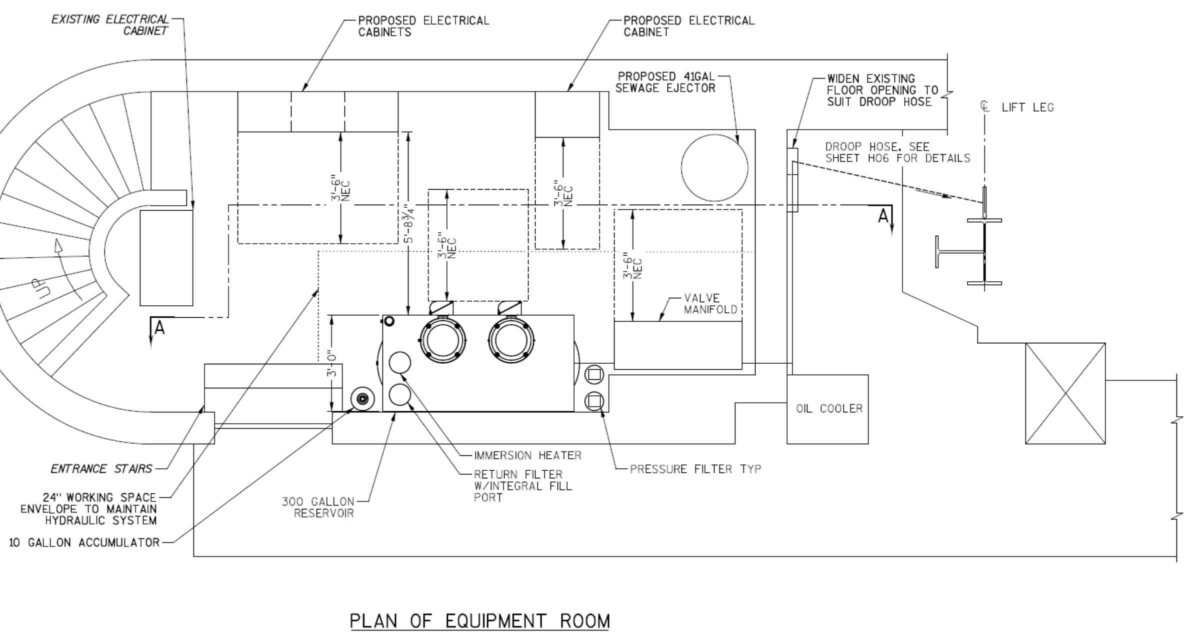

Photo 10: Plan of Equipment Room and Working Clearances

Cylinders

Given that buckling governs the cylinder design, the cylinders were gimbal mounted near the head of the cylinder to minimize the pin-to-pin length. The gimbal allows rotation in 2 planes ensuring that the cylinder will not see side loading when paired with its spherical rod end. The gimbal is a simple bolted construction and features shear registers to provide a robust design.

In the event of a hose burst, the counterbalance valves in the cylinder manifold prevent the span from falling. A trade-off of providing this protection is the cylinders can see live load, which can put additional wear and tear on seals and lead to leaks. With this in mind, for this bridge, the rod end design allows the cylinder to retract an addition ¾" to isolate the cylinder from any traffic loads.

Photo 11: Hydraulic Cylinder with the Span in the Fully Open Position

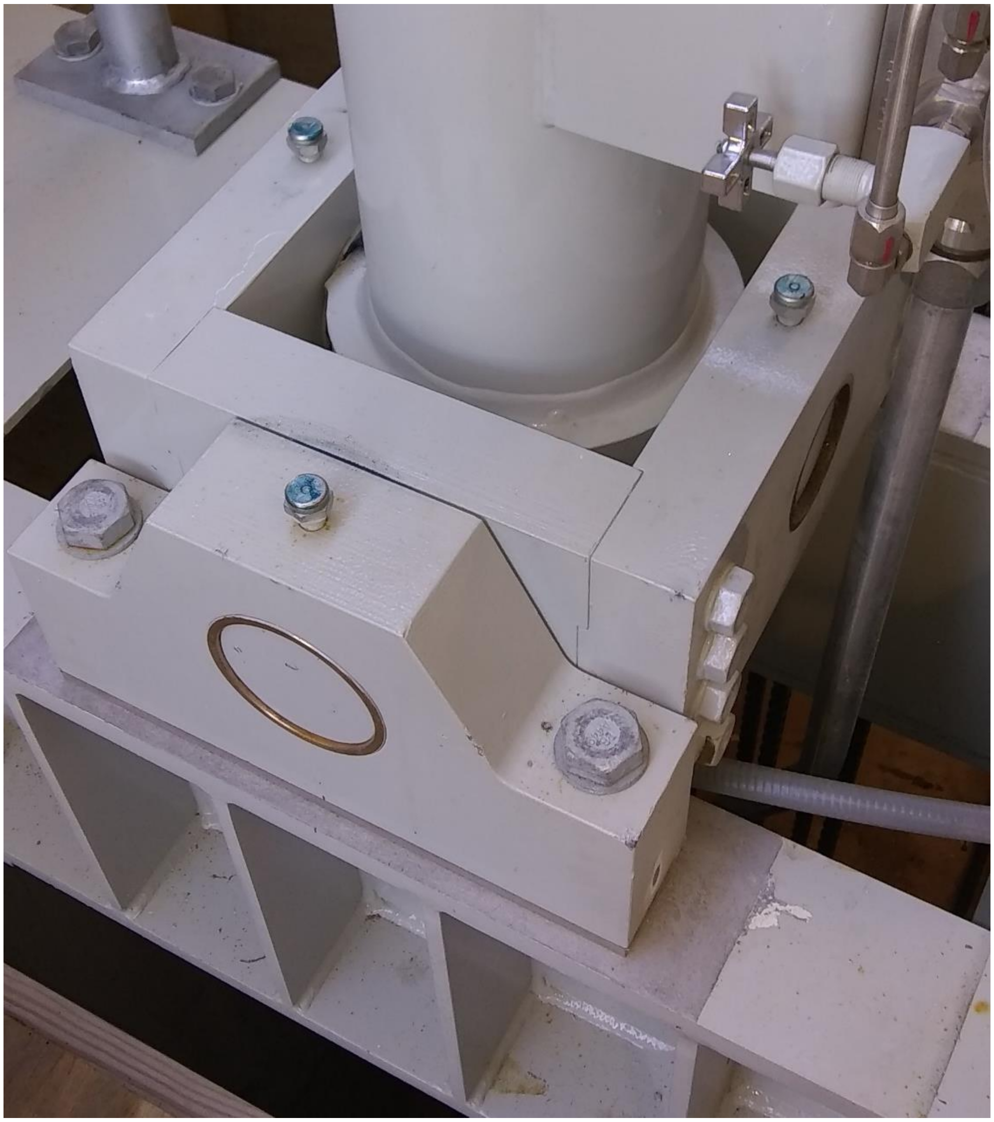

Photo 12: Hydraulic Cylinder Gimbal Mount

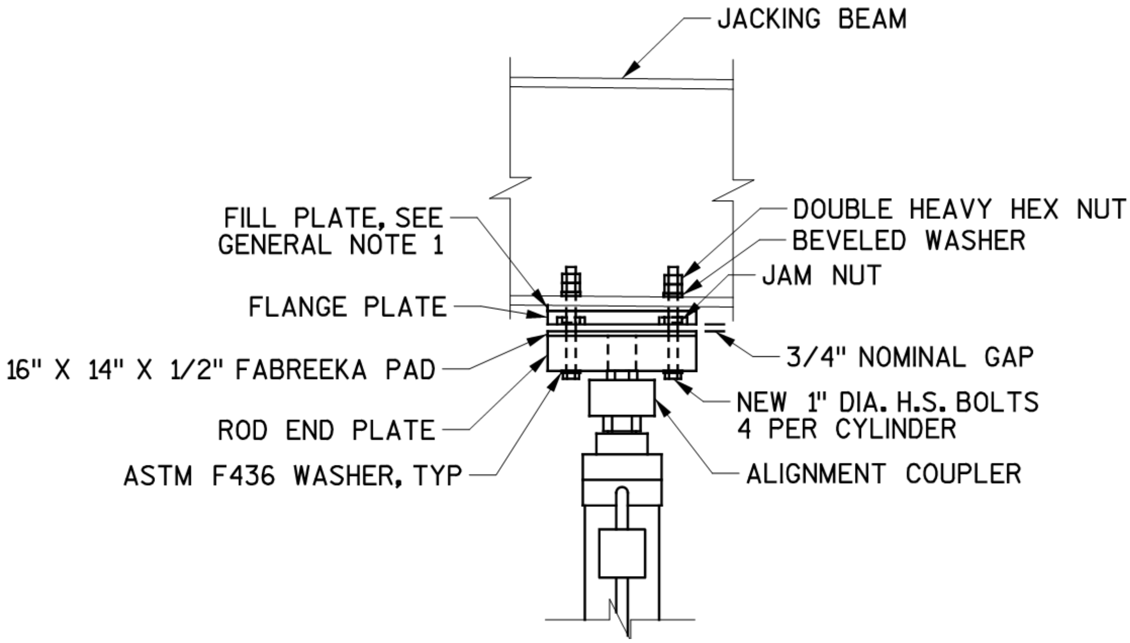

Photo 13: Rod End Details

HPU and control valve manifold

The hydraulic power unit consists of a JIC-style stainless steel reservoir, with two gear pumps mounted internal to the reservoir. The reservoir is 300 gallons. Practically speaking, that is the largest reservoir that would reasonably fit in the hydraulic room, but the reservoir was able to meet the size requirements of AASHTO, mainly due to the reduction in flow rate allowed by the regeneration circuit.

Photo 14: Hydraulic Power Unit

A stand-alone control valve manifold was provided. The manifold was arranged vertically to minimize the footprint given the size constraints of the hydraulic room. The manifold and control valve layout can be easily traced which simplifies troubleshooting, and a drawing of it is permanently mounted to the wall above the HPU. The control valves were provided with pilot chokes to minimize shock loading, which also reduces the likelihood of leaks.

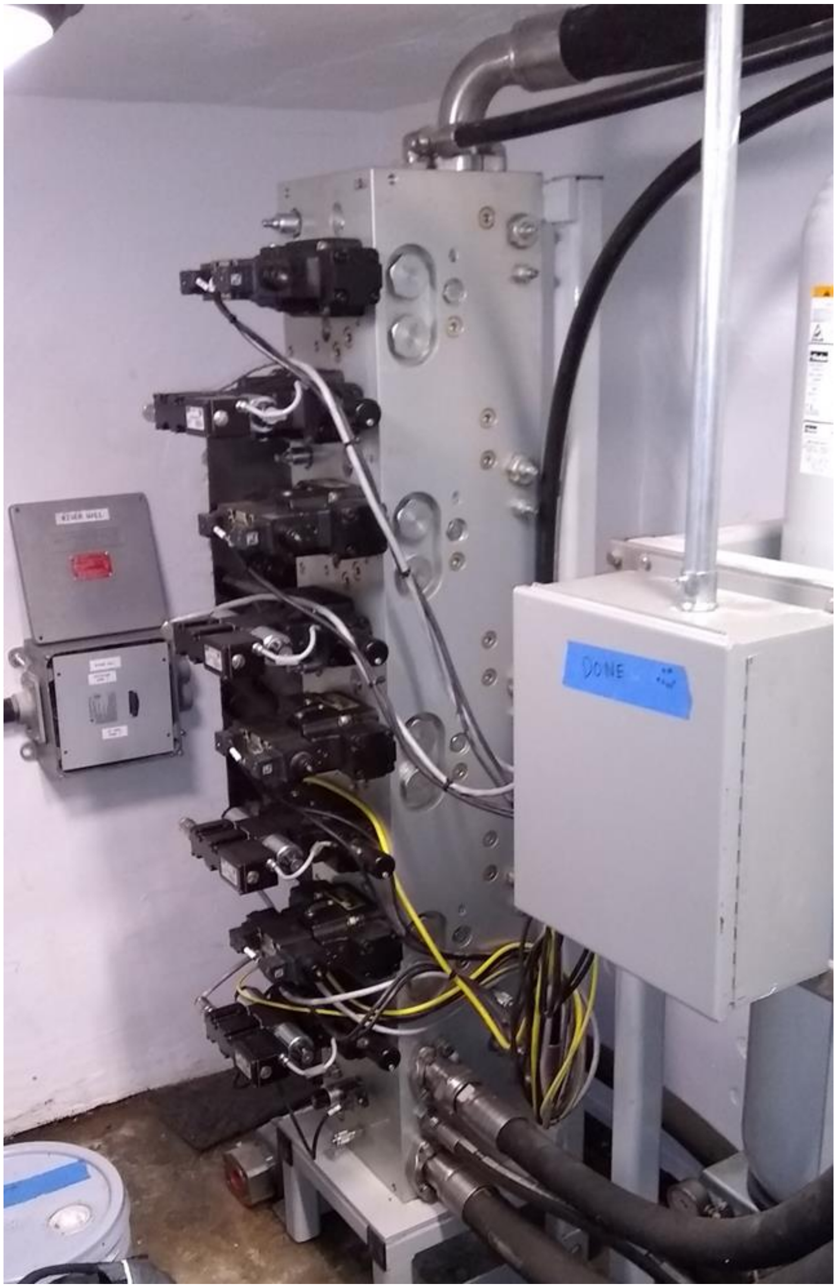

Photo 15: Control Valve Manifold

Proportional Control Valves

There are inherently unequal cylinder loads given the location of the cylinders with respect to the hydraulic power unit. In order to keep the cylinders synchronized proportional control valves were provided for each cylinder. The control system receives the position of the cylinders via linear displacement transducers. Based on the cylinder position, the proportional control valves restrict flow as needed to keep the stroke of the cylinders within +/- 1"by design. The proportional control valves also provide smooth acceleration/deceleration and creep speed. The valves are pilot operated given the flow rate of the pumps.

Redundancy Discussion

Given the number of openings for the bridge and the number of movable bridges along the waterway, the goal of the design was to provide the most robust and redundant system possible. Redundant features include dual pumps, the ability to support and lower the bridge on three cylinders, load holding valves on each cylinder, the capable of holding the bridge with 1 valve failed, additional rod seals and collar reservoir, soft seating via the control system or cylinder cushions, and an additional means to adjust system damping via an accumulator and needle valve.

In the event of a failure of a proportional control valve, there are redundant basic directional control valves adjacent to each proportional control valve. The flow is metered into these valves to make the pressure drop to each cylinder as close as practical and to allow the bridge to be operated at a slower speed in order to give the operator time to make skew adjustments. At the time of commissioning, only 1 adjustment, mid operation, was required to keep the system within skew, however it is expected that over time additional skew adjustments and/or adjustments to the needle valve may be required. Given that there are redundant flow paths, shuttle valves were provided to make sure that the return flow always goes through the correct control valve in the event a valve is taken out of service.

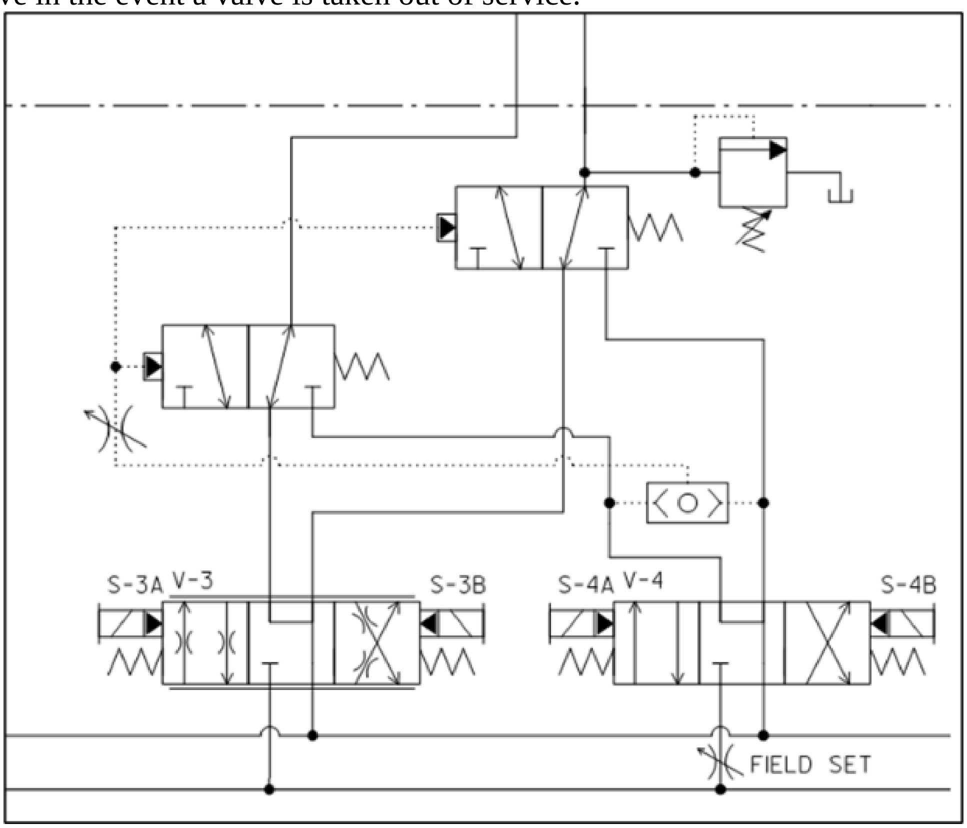

Photo 16: Redundant Control Valve Schematic

The cylinders are equipped with linear position transducers. A separate string potentiometer is provided to give the operator a second means of determining cylinder position and to ensure that the emergency mode of operation is independent from the main mode of operation.

Cooling Loop

Gear pumps were desired by the Owner due to their simplicity. One trade-off of using gear pumps is the hydraulic system is prone to generating heat when the flow is throttled. In addition, the larger than typical imbalance also generates heat, in particular with the up to 10 operation per hour requirement. Based on these considerations, a cooling loop was installed. Due to the low duty cycles of movable bridges, oftentimes cooling loops only operate when there are either design or operational issues. Because of this, it is often unknown if the cooling loop is actually functional. To address this shortcoming, the cooling loop was designed to always run during operation. This removes the heat caused by the inefficient features in the design and provides a positive indication that the cooling loop motor is functional. In the event of failure of the cooling loop, the reservoir is sufficiently sized to dissipate the heat generated during normal operation of the span for a limited number of cycles. In addition to save space and provide extra filtration the cooling loop can be used as a kidney loop, this helps prolong the equipment and oil life by keeping the oil cleaner than the minimum requirements.

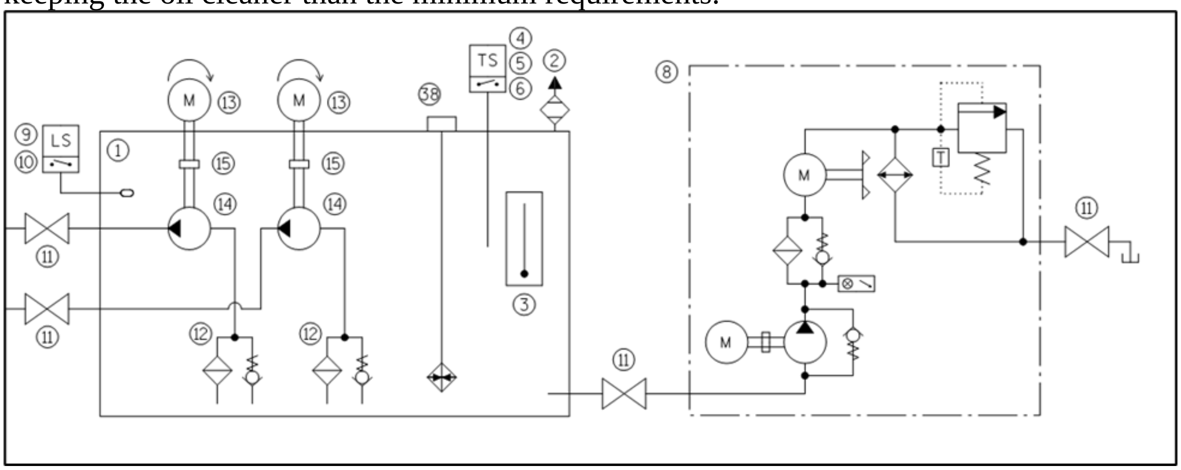

Photo 17: Cooling Loop Schematic

Piping System

There are a couple of items of significance with regard to the piping system. Since there is only one HPU, there had to be pipe runs across the span. This obviously presents several challenges. For the pipe run across the span, welded pipe was used to avoid having potential leaks in areas that are difficult to access, and to keep oil from dripping into the waterway.

Photo 18: Pipe Run Across the Span

Droop hoses were provided between the exterior of the hydraulic room and the movable span. The hoses were clamped to unistrut at three foot intervals, and 2 messenger cables were provided to reduce loading on the hoses and thereby extend their service life.

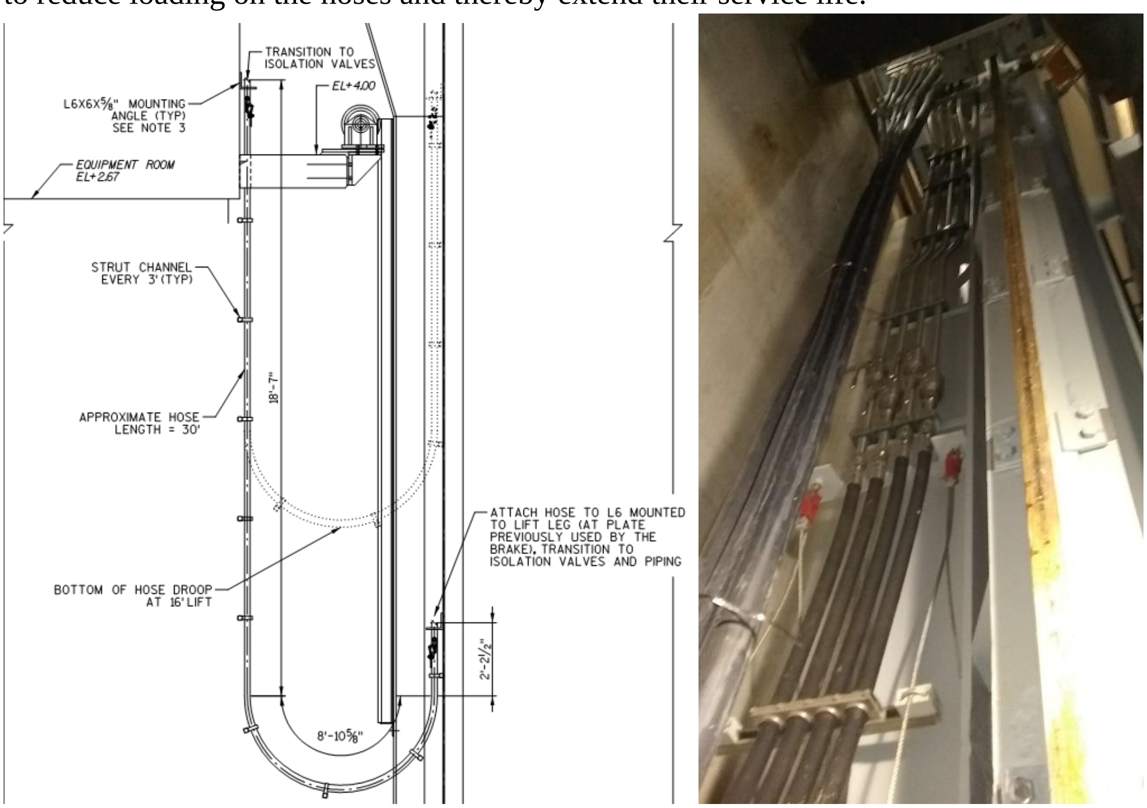

Photo 19: Droop Hose Design Details (left) and Attachment to the Span's Lift Leg (right)

Commissioning

Limited Shop Testing

The contract documents called for full shop testing, including testing of the control system when experiencing uneven loading, similar to the real loads to be seen at the bridge. Unfortunately, shop testing was scheduled to occur during the peak of the coronavirus pandemic. As a result, the decision was made to reduce the scope of shop testing to keep the project on schedule and reduce the health risks.

Field Testing

Since limited shop testing was performed, all the required testing had to be performed in the field. Once the Contractor had finished grooming the system and had it running reliably under ideal conditions, it was decided to test the system using unequal loads. To avoid having to partially disassemble the piping system to install valves to simulate uneven loading, the Contractor elected to test the system for uneven loading by parking a work truck on the span, favoring 1 corner. The system operated as intended with no skew issues. Tabletop vertical lift bridges by their nature do not really help cylinders stay synchronized. Given that the span was able to stay synchronized with large uneven loading demonstrates that proportional control can provide a sufficient level of control, not only for tabletop vertical lifts, but also for the majority of movable bridges and other heavy movable structures.

Photo 20: Field Testing Uneven Cylinder Loading with a Truck Parked on the Span

Installation Challenges and Lessons learned

Given the limited shop testing, some issues during installation and commissioning were to be expected. In reality, the limited shop testing extended the time spent grooming the bridge, but surprisingly, very few issues occurred during commissioning. The main issue was, near fully seated, during creep, the bridge was going rapidly out of skew. In addition, it was difficult to get a consistent gap between the jacking beam and the cylinder rod end. After discussions with the control systems integrator, it was discovered that they were using similar skew control logic that they would use for a tower drive vertical lift. In that control logic, the logic doesn't actively control skew near fully seated, since there is typically some error due to rope slip. After changing the logic to provide skew control for the entire operation, both the skew control issue and the gap between rod-end and jacking beam issue were resolved.

Conclusion

Many operation and safety improvements were made during the rehabilitation of this bridge and hydraulic system. A regeneration on demand circuit minimized the size of the pumps and reservoir, reducing the cost of the system, enabled it to fit withing the operators house, and providing a simple and robust means of increasing the available cylinder force. Maintainability was improved by removing failure-prone design details, using simple pumps, and keeping as many components as possible in conditioned spaces. Reliability was improved by providing multiple modes of operation not typically seen on a hydraulically operated movable bridge. Techniques from this bridge may be applicable to reduce the size and complexity of many other cylinder-based bridge designs while providing a very high level of robustness.
We would like to thank all of the team members who came together to make this project a success during these challenging times. Without their hard work and expertise, the project could not have been a success: The City of Milwaukee, Zenith Construction Group, MFP Automation and Engineering, as well as Panatrol Corporation, Mead and Hunt, Hardesty & Hanover LLC, and many more.